Transactions IAU, Volume XXIXA
Proc. XXIXA IAU General Assembly, August 2015
Thierry Montmerle, ed.

doi:10.1017/S1743921316000806

COMMISSION 12 SOLAR RADIATION AND STRUCTURE

RAYONNEMENT ET STRUCTURE SOLAIRE

PRESIDENT **Gianna Cauzzi**
VICE-PRESIDENT **Nataliya Shchukina**
PAST PRESIDENT **Alexander Kosovichev**
ORGANIZING COMMITTEE **Michele Bianda, Axel Brandenburg, Dean-Yi Chou, Sergio Dasso, Ming-De Ding, Stuart Jefferies, Natalie Krivova, Vladimir D. Kuznetsov, Fernando Moreno-Insertis**

TRIENNIAL REPORT 2012-2015

1. Introduction

Commission 12 of the International Astronomical Union encompasses investigations of the internal structure and dynamics of the Sun, the quiet solar atmosphere, solar radiation and its variability, and the nature of relatively stable magnetic structures like sunspots, faculae and the magnetic network. The Commission sees participation of over 300 scientists worldwide.

The IAU-wide re-organization effort of the last few years has resulted in the creation of 35 new Commissions providing a more up-to-date representation of contemporary astronomy. The three existing Commissions of Division E "Sun and Heliosphere" have been confirmed in existence with essentially unaltered scope, but their designation has been changed following the new convention that reflects their affiliation with a parent Division. Hence, the "historical" C12, C10 and C49 are now identified as C.E1 (Solar Radiation and Structure); C.E2 (Solar Activity); C.E3 (Solar Impact throughout the Heliosphere). In view of this designation change, we provide here below a brief history of Commission 12 throughout its over 50 years in existence.

In the following Sections, we further provide a review of the Commission activity in the 2012-2015 period, as well as of some important developments in the field. As always, such report is by no means exhaustive but reflects the main interests of the Commission Organizing Committee.

2. A Brief History of Commission 12

Solar Commissions were among the first scientific bodies of IAU. After its foundation in 1919, the First IAU General Assembly took place in Rome, Italy in 1922, with six of the original 32 Commissions devoted to solar phenomena. Among these was a C12 "Commission on the Solar Atmosphere", presided by Dr. G. E. Hale, with scientists such as G. Abetti, H. Deslandres, J. Evershed among its board members.

In the first reports of these Commissions, published in Vol. I of the "Transactions of the International Astronomical Union" (1922), the highly collaborative environment of

Table 1. Overview of Commission 12 leadership and triennial reports from 1961 onward (i.e. since the start of "IAU Transactions A" publications). Reports flagged with an asterisk are not currently available online.

Years	President and Vice President	ADS bibcode
1958–1961	L. Goldberg; —	*
1961–1964	R. Michard; M. N. Gnevyshev	*
1964–1967	R. Michard; M. N. Gnevyshev	*
1967–1970	M. N. Gnevyshev; R. G. Athay	1970IAUTA..14..111A
1970–1973	R. G. Athay; R. G. Giovanelli	1973IAUTA..15..129A
1973–1976	R. G. Giovanelli; M. K.V. Bappu	1976IAUTA..16b..55G
1976–1979	M. K.V. Bappu; Y. Uchida	1979IAUTA..17b..49B
1979–1982	Y. Uchida; R. W. Noyes	1982IAUTA..18...93U
1982–1985	R. W. Noyes; M. Kuperus	1985IAUTA..19...97N
1985–1988	M. Kuperus; J. W. Harvey	1988IAUTA..20...91K
1988–1991	J. W. Harvey; J. O. Stenflo	1991IAUTA..21...85H
1991–1994	J. O. Stenflo; F. L. Deubner	*1994IAUTA..22...85S
1994–1997	F. L. Deubner; P. V. Foukal	*1997IAUTA..23..149D
1997–2000	P. V. Foukal; S. Solanki	*2000IAUTA..24...65F
2000–2003	S. Solanki; T. Bogdan	*2003IAUTA..25...90S
2003–2006	T. Bogdan; V. Martìnez Pillet	2007IAUTA..26...89B
2006–2009	V. Martìnez Pillet; A. Kosovichev	2009IAUTA..27..104M
2009–2012	A. Kosovichev; G. Cauzzi	2012IAUTA..28...81K
2012–2015	G. Cauzzi; N. Shchukina	*this report*

the early IAU years was very prominent, with discussions among representatives of the largest observatories and institutions on the most pressing scientific questions of the time, and on how to best steer research in the different countries towards a common goal. For example, the 1922 C12 report states *"... the Committee believes that its first duty is to arrange for co-operation in the preparation and publication of solar statistics, ..."*, and proceeds to recommend that different phenomena continue to be recorded and published by different Institutes (such as the recording of sunspots' heliographic positions and areas at the Greenwich Observatory), and that international research is organized so to avoid un-necessary duplications (!).

The organization of international research, and description of the research activities performed in solar centers around the world (Kodaikanal, Arcetri, Pulkovo, Meudon, Mt. Wilson, etc.) continued to be an important part of the IAU triennal reports in subsequent decades. The name and numbering of solar Commissions however changed numerous times, following the evolution of solar astronomy; for example, by the 1950s C10 was titled *"Photospheric phenomena"*; C11 *"Outer solar atmosphere"*; C12 *"Solar radiation and spectroscopy"*; C13 *"Solar Eclipses"*; with various degrees of overlapping among the activities performed in each Commission (see also the summary of C10 history provided by Schrijver *et al.* 2015, in this Volume).

At the X IAU General Assembly in Moscow, in August 1958, a resolution was adopted to merge the scientific activities of Commission 10, 11, 12 and 13 into two Commissions, C10 *"Solar Activity"* and C12 *"Radiation and structure of the solar atmosphere"*. Since then, Commission 12 underwent one final name change in 1991, to *"Solar radiation and structure"* to acknowledge the growing field of helioseismology and internal solar structure as a crucial matter of interest for the Commission. This name has been maintained until its transition into Commission C.E1, during the most recent re-organization of IAU in 2015. Table 1 above lists the Presidents and vice-Presidents of Commission 12 from 1958 through 2015.

From the beginning of the Triennial IAU publication “Reports in Astronomy” (IAU Transactions A) in 1961, Commission 12 and its fellow solar commissions (C10 and, from 1974, also C49) have faithfully reported on important topics and developments in the field, as well as on world-wide activities. With the rapid growth of the discipline however, such a task has become increasingly difficult, as comprehensively described by Schrijver *et al.* (2015) in this Volume (already in the early 1960’s, the bibliographical references in the reports amounted to several pages!). Page limitations imposed by the Executive Committee of the IAU further compounded on the problem; to this end it is quite interesting to read the introductory statements of Athay *et al.* (1970). As a result, observatories’ activities have gradually disappeared from the reports, and comprehensive writings have given way to more subjective summaries of the many scientific topics debated in the community, as selected by the Organizing Committees of the Commission. Even with such limitations, the collective insight afforded by over 50 years of reports from the solar commissions of IAU provides a formidable compendium of the development of our discipline.

3. Commission 12 Organizational Activities 2012-2015

During the last triennium, Commission 12 proposed and organized several IAU meetings, in particular the IAU symposium 294 *“Solar and astrophysical dynamos and magnetic activity”* and the Special Session 6 *“Science with large solar telescopes”* during the XXVIII General Assembly in Beijing (August 2012); and the Focus Meeting 13 *“Brightness variations of the Sun and Sun-like stars”* and the IAU Symposium 320 *“Solar and Stellar Flares and Their Effects on Planets”* during the last General Assembly in Honolulu (August 2015). Especially during the last GA, a large interdisciplinary audience was in attendance of the meetings, with much interaction and feedbacks from solar and stellar astrophysicists.

Commission 12 also contributed to the organization of IAU Symposium 300 *“Nature of prominences and their role in space weather”* (Paris, June 2013), and Symposium 305 *“Polarimetry: The Sun to Stars and Stellar Environments”* (Costa Rica, December 2014). The latter was the first IAU Symposium held in Central America (Costa Rica became an IAU member state in 2012) and the first devoted to polarimetry as a cross-disciplinary technique of large relevance throughout many branches of astrophysics. Two future IAU Symposia sponsored by the Commission will also be held in South America in October 2016, IAUS 327 *“Fine Structure and Dynamics of the Solar Atmosphere”* (Cartagena de Indias, Colombia) and IAUS 328 *“Living around Active Stars”* (Maresias, Brasil).

Finally, Commission 12, together with Commissions 10 and 49 of Division E, submitted and defended the proposal for the continuation of the Commissions in the new IAU structure.

4. New Observational Facilities

Numerous new observing facilities have come online in the last few years, both from the ground and space. We give a brief overview of some of them.

After the commissioning of the 1.6 m New Solar Telescope at Big Bear Solar Observatory, other large-diameter telescopes operating in the visible and near-IR have come online in the last triennium. The New Vacuum Solar Telescope (NVST), a 1-m telescope with an adaptive optical system at Fuxian Lake in the southwest of China, has been operated to provide high resolution imaging and spectral observations (Liu *et al.* 2014), which have promoted a number of researches on fine solar structures (Yang *et al.* 2014;

Yan *et al.* 2015). A multi-wavelength solar telescope, named "Optical and Near-infrared Solar Eruption Tracer" (ONSET), has also been built at the same place to acquire high cadence solar images in He I 10830 Å, Hα and white-light (Fang *et al.* 2013). The German GREGOR, an open, on-axis 1.5 m telescope, has been inaugurated in mid-2012, and commenced scientific operation in 2014. First results have been presented during the IAU General Assembly in Honolulu, describing the action of slipping reconnection on a flare development, as evidenced by features resolved at the 0.1" spatial scale (Sobotka *et al.* 2015). Efforts have also continued for the design and planning of the 2-m Indian New Large Solar Telescope (NLST), and the 4-m European Solar Telescope (EST). The US-led 4-m, off-axis Advanced Technology Solar Telescope (ATST) has undergone very fast development in the last few years. After breaking ground in late 2012, construction has proceeded rapidly on top of Haleakala (Maui, Hawai'i) and the telescope, now renamed the Daniel K. Inoyue Solar Telescope (DKIST) is slated for first light in 2019 (Rimmele *et al.* 2015). DKIST will allow spectro-polarimetry of solar features at unprecedented spatial and temporal resolution, as well as the first exploration of the faint solar corona and its magnetic field in the 1-5 μm range. A view of the construction can be seen at http://dkist.nso.edu.

The balloon-borne solar observatory SUNRISE flew for the second time in June 2013. Equipped with a 1 m aperture Gregory telescope, SUNRISE could make observations of both quiet and active solar features free of atmospheric disturbances. First analyses of data from this second flight were carried out by Riethmüller *et al.* (2013) and Danilovic *et al.* (2014), and included comparison of the first high-resolution images of quiet Sun, active region plage, and sunspots in the Mg II k 279.6 nm line with images recorded in the core of the Ca II H line.

Several sounding rockets also obtained important results in the triennium. The High Resolution Coronal Imager (Hi-C) instrument launched July 11, 2012. With a single narrowband EUV channel centered on 193 Å and a 0.1"/pixel scale, Hi-C collected the highest resolution images of the solar corona to date, and demonstrated that at 150 km resolution we might be approaching the scale size of coronal structures. Results of Hi-C include the observations of magnetic braids in an active region that are reconnecting, relaxing and dissipating sufficient energy to heat the structures to about 4 MK (Cirtain *et al.* 2013), and the rapid variability of moss interpreted as a signature of coronal nanoflares (Testa *et al.* 2013). The nanoflare hypothesis for coronal heating is also strongly supported by the results of the Extreme Ultraviolet Normal Incidence Spectrograph (EUNIS-13) sounding rocket instrument. During the 2013 April 23 flight, EUNIS clearly observed the Fe XIX 592 Å line in large parts of a *quiescent* active region, unambiguously indicating the presence of plasma at 10 MK temperatures (Brosius *et al.* 2014). Finally, the Chromospheric Ly-Alpha SpectroPolarimeter (CLASP) sounding rocket successfully launched in September 2015. The goal of CLASP was to measure the scattering polarization signal of the H I Ly-α line, and to use it to retrieve information about the magnetic fields present in the upper chromosphere (Ishikawa *et al.* 2015). During the five minutes of observing time, scattering polarization signal of the Ly-α line was clearly measured for the first time. The first preliminary results seem to confirm the theoretical predictions of Trujillo Bueno *et al.* (2011, 2012). In particular, the observed linear polarization Q/I profile seems to show the expected signatures of phenomena such as the effects of quantum intereference between different fine structure J-levels, and the impact of partial frequency redistribution (PRD; see also Sect. 8).

The NASA SMEX Interface Region Imaging Spectrograph (IRIS De Pontieu *et al.* 2014) was successfully launched in June 2013, and has operated uninterruptedly since. To fulfill its primary goal of understanding the complex chromosphere/transition region/corona interface, IRIS employs a high resolution UV imaging spectrograph providing spectra in the FUV and NUV ranges (1300–1400 Å, and 2780–2835 Å, respectively) at a spatial resolution of 0.33", and temporal cadence as high as a few seconds. Concomitant slit jaw images of up to 120"×120" are acquired in four different UV passband centered on interesting chromospheric and transition region diagnostics such as C II, Si IV, Mg II h&k. A very versatile mode of operation allows IRIS to tailor each observation sequence to a specific scientific problem. Recent results from analysis of IRIS data have shed light, among others, on the presence of spicules in the upper solar atmosphere; on the presence of hot pocket of plasma at surprisingly low altitudes above the solar surface; on the role of accelerated particles in heating coronal loops; on the dynamics and evolution of flaring kernels (Pereira *et al.* 2014; Peter *et al.* 2014; Testa *et al.* 2014; Tian *et al.* 2014a; Graham & Cauzzi 2015). A large database of varied IRIS observations has been accrued to date, and is freely available for investigations.

The Atacama Large Millimeter/submillimeter Array (ALMA) has recently commenced operation on the Chajnantor plateau in the Chilean Andes at an altitude of 5000 m. Regular *solar* observations with ALMA are expected to start in Cycle 4 (2016) after the initial solar observing modes have been demonstrated. ALMA will thus allow for a powerful and novel probe into the solar chromosphere, where most of the sub-millimeter radiation originates (Wedemeyer *et al.* 2015). An international scientific network has been initiated in order to prepare for use and exploitation of the ALMA solar data: the "Solar Simulations for the Atacama Large Millimeter Observatory Network" (SSALMON, http://www.ssalmon.uio.no/). Based on first solar test observations, the network is developing strategies for regular solar campaigns; and analyzing state-of-the-art numerical simulations of the solar atmosphere, including modeling of instrumental effects to constrain and optimize future observing modes.

The Solar Orbiter, selected in October 2011 as the first medium-class mission of ESA's Cosmic Vision 2015-2025 Programme, is now scheduled for launch in October 2018. The mission is led by ESA, with important contributions by NASA. The spacecraft will take just under three-and-a-half years to reach its highly elliptical orbit around the Sun, that will get it as close as 43 million km, i. e. ∼60 solar radii from the solar surface. During the seven-year mission, its suite of 10 instruments (both *in-situ* and remote sensing) will measure the solar wind plasma, fields, waves, and energetic particles close enough to the Sun to avoid complexities introduced by transport and propagation processes. The solar community is also eagerly anticipating the first direct observation of the polar regions of the Sun, in particular of the polar magnetic fields around the expected time of polarity reversal.

Stage B of the Russian Interhelioprobe Mission was continued in 2011-2014. The sketch design of the mission was completed and the stage of instrumentation manufacturing is started. Similar to Solar Orbiter, the mission is aimed at the study of the inner heliosphere and the Sun at short distances and out-of-ecliptic. Interhelioprobe observations in the immediate proximity to the Sun combined with in-situ plasma measurements will contribute significantly to the solution of the problems of heating of the solar corona, solar wind acceleration, and the origin of major solar active events such as solar flares and coronal mass ejections (Kuznetsov *et al.*, 2016).

5. Research Highlights: Solar irradiance

Variations in the solar total (integrated over all wavelengths; TSI) and spectral (SSI) irradiance have been monitored from space for almost fours decades. A brief overview of the space-based experiments that measured solar total and spectral irradiance in the

Table 2. Summary of solar irradiance measurement experiments in 2012–2015

Spectral range	Experiments	References
TSI	SoHO/VIRGO, ACRIM-3, SORCE/TIM, PSat-3/TCTE, Picard/PREMOS	Fröhlich (2012); Willson (2014); Kopp (2014); Schmutz *et al.* (2013)
SSI: UV-IR	SORCE/SIM, SORCE/SOLSTICE, ISS/SOLSPEC, Picard/PREMOS	Harder *et al.* (2009); Snow *et al.* (2010); Thuillier *et al.* (2014b,a)
SSI: XUV-FUV	TIMED/SEE, SDO/EVE, ISS/SolACES, NOAA GOES, PROBA2/LYRA	Woods *et al.* (2005, 2012); Thuillier *et al.* (2014a); Schmidtke (2015); Dominique *et al.* (2013)

period 2012–2015 is given in Table 2. The variability is of the order of 0.1% in the TSI and in the visible domain, while it increases to 10–100% towards Ly-α. Further in the EUV, solar radiation changes by a factor of ten over the course of the solar cycle. On time scales longer than a day, the variability is dominated by the evolution of the photospheric magnetic field (Domingo *et al.* 2009; Solanki *et al.* 2013).

Three main questions have been specifically addressed over the last several years: (1) the absolute level of the TSI, (2) the spectral distribution of the irradiance variability, and (3) the magnitude of the secular change.

The value of TSI of $1360.8 \pm 0.5\,\mathrm{Wm}^{-2}$ recorded by SORCE/TIM during the 2008 solar minimum was significantly lower than the earlier accepted value of $1365.4 \pm 1.3\,\mathrm{Wm}^{-2}$. Careful analysis of instrumental uncertainties and additional tests revealed that scattered light and measured optical power were responsible for the difference (Fehlmann *et al.* 2012; Kopp 2014; Willson 2014). The appropriate corrections bring individual data sets to about the same level, apparently resolving this long-standing issue.

A debate on the spectral profile of the irradiance variability, and in particular on the amplitude and phase of the variability in the UV (200–400 nm) and visible (400–700 nm), respectively, has been triggered by the data from SORCE/SIM and SORCE/SOLSTICE (Harder *et al.* 2009). These measurements suggested a factor of $\sim 3 - 10$ stronger variability in the UV than expected from all earlier measurements and models, partly compensated by the variability in the visible range, in anti-phase with the solar activity cycle (and TSI). Multiple data- and model-driven studies have consolidated the view that the discrepancy is due to the remaining uncorrected instrumental issues (Deland & Cebula 2012; Ermolli *et al.* 2013; Wehrli *et al.* 2013; Marchenko & DeLand 2014; Ball *et al.* 2014; Morrill *et al.* 2014; Yeo *et al.* 2014, 2015). Inverse solar cycle irradiance variability in the visible was indeed observed in models if *only* continuum wavelengths were taken into account (Criscuoli & Uitenbroek 2014; Shapiro *et al.* 2015). However, as the amplitude and, on the 11-year activity time scale also the phase of the variability are defined by changes in spectral lines, the overall changes in the irradiance still follow the magnetic activity cycle (Shapiro *et al.* 2015).

Finally, long-term (centuries and longer) irradiance reconstructions produced before 2012 were discussed by Solanki *et al.* (2013). The estimates of the magnitude of the TSI increase between the Maunder minimum and now cover the range $0.8 - 3\,\mathrm{Wm}^{-2}$, whereby most models converge to values around $0.8 - 1.7\,\mathrm{Wm}^{-2}$. Models of the long-term irradiance variability have been recently published by Bolduc *et al.* (2014) and Dasi-Espuig *et al.* (2014). Bolduc *et al.* (2014) combined a data-driven Monte Carlo model of the evolution of active regions with an empirical secular modulation of the quiet-Sun emissivity to reconstruct the UV irradiance back to the 17th century. Dasi-Espuig *et al.* (2014) combined the surface flux transport simulations of the active region evolution with the evolution of ephemeral regions based on the concept of extended and overlapping cycles (Wilson *et al.* 1988) to reconstruct the TSI since 1878. Although exact estimates of the TSI change since 1700 are not given, both reconstructions imply long-term trends consistent with the range given by the majority of the earlier models (cf. Fig. 17 in Usoskin *et al.* 2015).

Finally, Zolotova & Ponyavin (2015) claimed recently that the Maunder minimum (1645–1715) was not as deep as usually believed. However, Usoskin *et al.* (2015) have carefully re-assessed all available data and other pieces of evidence to conclude that solar activity was indeed unusually low during this period corresponding to a grand minimum state.

6. Research Highlights: The Solar Composition

The solar photospheric abundance of oxygen is still a matter of debate. For about ten years a low oxygen abundance as inferred by Asplund *et al.* (2004) caused significant discrepancies between the standard solar model and helioseismology, leading to far-reaching implications in many areas of astrophysics. The reliability of these results has been investigated in several papers, most recently by Caffau *et al.* (2015); Fabbian & Moreno-Insertis (2015); Socas-Navarro (2015). Caffau *et al.* (2015) analyzed several solar observations of the the centre-to-limb variation of the forbidden [O I] line at 630 nm in order to separate the individual contributions of oxygen and the blended Ni I line. By comparing the observations with line formation computations performed on a CO5BOLD 3D hydrodynamical simulation of the solar atmosphere, they obtained a consistent fit indicating a rather low oxygen abundance of $A(O)=8.730 \pm 0.05$. This, however, remains discrepant with the abundance derived with other lines, including the subordinate [O I] line at 636 nm. Socas-Navarro (2015) presented instead a new determination obtained by fitting the blend at 630 nm with an observational 3D model. The resulting best-fit abundances are $A(O)=8.90$ and $A(Ni)=6.15$. Nevertheless, introducing minor tweaks in the model and the procedure, it is possible to retrieve very different values, even down to $A(O)=8.70$. This extreme sensitivity of the abundance to possible systematic effects probably reflects the real uncertainty inherent to all abundance determinations based on a prescribed model atmosphere. In addition, the role of magnetic fields in the Sun's photosphere remains ill-understood. Fabbian & Moreno-Insertis (2015) investigated its effect in terms of the influence of magnetic structures on the continuum intensity at different viewing inclination angles, and on the intensity profile of two [O I] spectral lines. Using the RH numerical radiative transfer and 3D magnetoconvection models, a good match of the synthetic disk center continuum intensity to the absolute continuum values from the FTS observational spectrum was obtained. Their results indicate that magnetic fields lead to non-negligible changes in the synthetic spectrum, with larger average magnetic flux causing the lines to become noticeably weaker, and the derived photospheric oxygen abundance correspondingly lower by a few to several centidexes.

In a series of papers, Scott *et al.* (2015a,b) and Grevesse *et al.* (2015) presented a comprehensive re-determination of the solar composition, investigating all ingredients of the analysis across all elements, to obtain the most accurate, homogeneous and reliable results possible. The derived abundances for the intermediate mass elements from Na to Ca appear systematically smaller than most previous ones derived with 1D semi-empirical models, while the ones derived for the iron group elements Sc to Ni (and, to a measure, for the heavy elements from Cu to Th) well agree with meteoritic abundances. Spectra from the RESIK Bragg soft X-ray spectrometer flown aboard the Russian CORONAS-F have instead been used to analyze the composition of solar plasma at temperatures T > 3 MK. Si and S abundances were determined in both flare and active regions plasma. The preferred S abundance determination was close to photospheric and to quiet-Sun solar wind (Sylwester *et al.* 2012), while the Si abundance was confirmed much enhanced in flares with respect to the photospheric one (Sylwester *et al.* 2013). Both results were confirmed by soft X-ray observations obtained with the Indian Chandrayaan-1 (Narendranath *et al.* 2014), but have been somewhat recently revised by Sylwester *et al.* (2014) by using deviations from the assumption of isothermal plasmas.†

7. Research Highlights: Helioseismology

Salabert *et al.* (2015) investigated the response of the solar acoustic oscillations to solar activity in order to provide insights into the structural and magnetic changes in the sub-surface layers of the Sun during the recent sunspot cycles. The analysis of 18 years of continuous observations of the solar acoustic oscillations from the GOLF instrument on board the SoHO spacecraft showed that. the low-frequency modes reveal a time evolving signature of the quasi- biennial oscillation, which is particularly visible for the quadrupole component indicating on the presence of a complex magnetic structure. It is concluded that the structural and magnetic changes responsible for the frequency shifts remained comparable between Cycle 23 and Cycle 24 in the deeper subsurface layers below 1400 km as revealed by the low-frequency modes. However, the frequency shifts of the higher-frequency modes, sensitive to shallower regions, show that Cycle 24 is magnetically weaker in the upper layers of Sun. Reiter *et al.* (2015) developed a new methodology for measuring properties of the solar oscillation modes, which is equally well suited for the estimation of low-, medium-, and high-degree mode parameters from m-averaged solar oscillation power spectra of widely differing spectral resolution. Application of this method to the 66-day 2010 Solar and Heliospheric Observatory/MDI Dynamics Run revealed pronounced departure of the sound speed in the outer half of the solar convection zone and in the subsurface shear layer from the radial sound speed profile contained in Model S of Christensen-Dalsgaard and his collaborators that existed in the rising phase of Solar Cycle 24 during mid-2010. The helioseismic determination of the solar age has been a subject of several studies because it provides us with an independent estimation of the age of the Solar System. Bonanno & Fröhlich (2015) presented the Bayesian estimates of the helioseismic age of the Sun, which are determined by means of calibrated solar models that employ different equations of state and nuclear reaction rates. It is shown that the most constrained posterior distribution of the solar age for models employing Irwin EOS with NACRE reaction rates leads to 4.587 ± 0.007 Gyr, while models employing the Irwin EOS and Adelberger *et al.* (2011) reaction rate give 4.569 ± 0.006 Gyr. Substantial effort was made to determine the structure and variations of the meridional circulation and zonal flows ('torsional oscillations'). Meridional flow in the solar interior plays an important role in redistributing angular momentum and transporting magnetic flux inside the Sun. Using the first 2 yr of continuous helioseismology observations from the Solar Dynamics Observatory/Helioseismic Magnetic Imager and the time-distance helioseismology technique, (Zhao *et al.* 2013) analyzed travel times of acoustic waves that propagate through different depths of the solar interior. After remov-

---

† The RESIK data is available in the public domain, at `http://www.cbk.pan.wroc.pl/experiments/resik/resik_level2.php`.

ing a systematic center-to-limb effect in the helioseismic measurements (Zhao *et al.* 2013) and performing inversions for flow speed, it was found that the poleward meridional flow of a speed of 15 m s^{-1} extends in depth from the photosphere to about 0.91 $R_\odot$. The analysis revealed the existence of a second meridional circulation cell below the shallower one. The discovery of the double-cell meridional circulation profile with an equatorward flow shallower than previously thought has important implications for dynamo models of the solar cycle. Similar analysis performed by Kholikov *et al.* (2014) using several years worth of Global Oscillation Network Group Doppler data suggested a partial evidence of a sign change in the travel-time differences at mid-convection zone depths. This analysis on an independent data set using different measurement techniques strengthens the conclusions of Zhao *et al.* (2013) and Schad *et al.* (2013a) that the convection zone may have multiple cells of meridional flow. Variations of the meridional flow speed, associated with large-scale converging flows around active regions, are considered as a key mechanism regulating the strength of the solar cycles (Hathaway & Upton 2014). These variations were studied by Komm *et al.* (2015b,a); Zhao *et al.* (2014). A surprising result is the absence of high-latitude branches of the torsional oscillations in Solar Cycle 24. This led to suggestions that the next solar cycle will be even weaker than the current cycle. In addition, the subsurface flows show a significant hemispheric asymmetry, particularly, the faster zonal band in the torsional-oscillation pattern in the northern hemisphere is located closer to the equator than the band in the southern hemisphere and migrates across the equator when the magnetic activity in the southern hemisphere is reaching maximum. The meridional-flow speed decreases substantially with the increase of magnetic activity, and the flow profile shows two zonal structures in each hemisphere. The residual meridional flow, after subtracting a mean meridional-flow profile, converges toward the activity belts and shows faster and slower bands like the torsional-oscillation pattern. More interestingly, the meridional-flow speed above latitude 30 degrees shows an anti-correlation with the poleward-transporting magnetic flux, slower when the following-polarity flux is transported and faster when the leading-polarity flux is transported. It is expected that this phenomenon slows the process of magnetic cancellation and polarity reversal in high-latitude areas. Hathaway (2012) suggested that supergranules of different sizes can be used to probe the rotation rate in the Sun's outer convection zone. They found that the equatorial rotation rate as a function of depth as measured by global helioseismology matches the equatorial rotation as a function of wavelength for the supergranules. These characteristics indicate that probing the solar convection zone dynamics with supergranules can complement the results of helioseismology. In particular, it was found evidence for giant cellular flows that persist for months by tracking the motions of supergranules. As expected from the effects of the Sun's rotation, the flows in these cells are clockwise around high pressure in the north and counterclockwise in the south (Hathaway *et al.* 2013). Helioseismology observations have not confirm this result, but an evidence for persistent large-scale flows has been found from analysis of the GONG and HMI data(Howe *et al.* 2015).

8. Research Highlights: Solar spectropolarimetry

Solar spectro-polarimetry is steadingly evolving as a topic of large relevance. In the last few years, large efforts have been directed towards the development of novel diagnostic methods for the investigation of magnetic fields in domains not accessible through the conventional techniques based on the Zeeman effect. These are starting to make possible the determination of magnetic fields at scales below the resolution of telescopes, as well as in the very dynamical outer solar atmosphere.

8.1. *Photosphere*

The solar inter-network magnetic field is the weakest component of solar magnetism, yet it appears to contribute a relevant fraction of the solar surface magnetic flux. Gošić *et al.* (2014), analyzing long duration observations obtained with *Hinode*, determined that at any given time the internetwork fields account for about 15% of the total quiet Sun flux. More importantly, the inter-network fields would be able to replace the entire flux present in network features in approximately 18-24 hr. Again by analyzing *Hinode* data, covering the period from solar minimum to maximum of cycle 24, Jin & Wang (2015) found that the flux density of the solar inter-network field is essentially invariant, 10 ±1 G, suggesting that the inter-network magnetic field does not arise from flux diffusion or flux recycling of solar active regions.

These results are consistent with the investigations of Bianda *et al.* (2014) and Ramelli *et al.* (2015), aimed at assessing the presence and relevance of quiet Sun magnetic fields, tangled on scales smaller than the resolution element of solar telescopes. In 2007, near the minimum of the solar cycle, a synoptic program was in fact started at the Istituto Ricerche Solari Locarno (Switzerland) with the aim of exploring possible variations of such hidden magnetic flux with the solar cycle, by applying a differential Hanle effect technique on observations of scattering polarization in C2 molecular lines in the region around 514.0 nm (Kleint *et al.* 2011). The observations obtained up to now, which include the recent maximum of the solar activity, don't show large variations of the turbulent unresolved magnetic field. This provides important hints on the existence of a local dynamo effect at granular and sub-granular scales, uncorrelated with the global magnetic field varying with the solar cycle.

The high resolution data from the vector magnetograph IMaX on SUNRISE (Martínez Pillet *et al.* 2011) were used for several studies regarding the magnetic structure of network elements and bright point. Martínez González *et al.* (2012) investigated the internal magnetic structure of a quiet-Sun network element. Their results are consistent with an expanding magnetic canopy, i. e. a region where the LOS passes through the magnetized atmosphere of the expanding flux tube in the upper photosphere, then hits the nearly field-free atmosphere below the canopy before penetrating the $\tau = 1$ surface and entering the convection zone.

The positions of a set of bright magnetic elements were determined by Jafarzadeh *et al.* (2014) from SUNRISE images recorded in different spectral bands. An estimate of the formation height of these spectral bands provided the inclinations of the magnetic elements from a direct geometrical method. This method returned that the magnetic field in BPs is nearly vertically oriented with a narrow distribution. In contrast, the traditionally used inversions of Stokes profiles provided an almost horizontal field for the same set of magnetic elements, probably due to the effects of noise in the linear polarization signals in Stokes Q and U. The almost vertical orientations of the magnetic field in BPs were confirmed by a study of Riethmüller *et al.* (2014), who compared BP properties between SUNRISE observations and magnetohydrodynamical simulations.

8.2. *Chromosphere and transition region*

In the weak field environments of the outer solar atmosphere, diagnostics methods much rely on the analysis of scattering polarization and the Hanle effect.

Aided by much theoretical progress (see below, and the discussion in Lagg *et al.* 2015) the combined action of the Hanle and Zeeman effect has been used in the last few years to provide first accurate measurements of chromospheric magnetic fields, using two sets of spectral lines in particular: the Ca II and He I infrared triplets. Schad *et al.* (2013b) presented an analysis of the properties of super-penumbral fibrils as observed in He I

1083 nm with the FIRS instrument at the Dunn Solar Telescope: they found that the fibrils have horizontal fields of less than 300 G and, importantly, that the direction of the fields does not deviate significantly from the visible structures, as observed typically in Hα or other chromospheric signatures. Similar results were obtained by de la Cruz Rodríguez & Socas-Navarro (2011), using the Ca ii diagnostics. In a continuation study, Schad *et al.* (2015) revealed how the super-penumbral magnetic field appears to be only coarsely structured, unlike the observed intensity structure, suggesting that fibrils are not concentrations of magnetic flux, but are instead distinguished by individualized thermalization.

Orozco Suárez *et al.* (2014) analyze He i 1083 nm polarimetric measurements in a prominence, and find a mean field strength of 7 G, with an averaged magnetic field inclination with respect to the local vertical of over 70°. The field presents modest spatial variations except being on average lower in the prominence body than in the prominence feet. The same authors tackled the difficult observations of magnetic fields in the highly dynamic spicules, and show that the average magnetic field strength at the base of solar spicules is about 80 G, rapidly decreasing to about 30 G at a height of 3000 km above the visible solar surface (Orozco Suárez *et al.* 2015).

Theoretical work is starting to address the scattering polarization signals of Ly-α and of several other strong resonance lines, which are deeply affected by Partial Redistribution (PRD) effects. While a self-consistent theoretical approach is currently available only for the simplest case of a two-level atom (Bommier 1997a,b), during the last few years strong efforts have been devoted to the development of a PRD theory suitable for treating more complex multi-level atomic systems. The main problem, which still awaits for a well-established solution, concerns the necessity of describing in a self-consistent way the various effects of collisions with neutral perturbers (namely the broadening of the spectral lines), the modification of atomic polarization (in general a depolarization), and the frequency redistribution during the scattering process. Important progresses, on the other hand, have been made in the treatment of the limit of coherent scattering in the atom rest frame (collisionless regime).

A particularly interesting result is the one recently achieved by Casini *et al.* (2014): through a new formulation of the quantum problem of coherent scattering of polarized radiation, these authors derive a generalized frequency redistribution function for a two-term atom (i.e., an atomic model accounting for quantum interference between different fine-structure levels), in an arbitrary magnetic field. Previously, two approaches were generally applied to treat coherent scattering processes in the atom rest frame: the one based on the Kramers-Heisenberg scattering formula (see Stenflo 1994), and the one based on the metalevel picture (Landi Degl'Innocenti *et al.* 1997). The former approach has been extensively applied by the group of the Indian Institute of Astrophysics (Bangalore, India) to treat increasingly complex atomic models (e.g., multi-term atoms, atoms with hyperfine structure) in various regimes of the magnetic field (Smitha *et al.* 2011, 2012a,b, 2013; Sowmya *et al.* 2014)S; the latter has been used by the group of the Instituto de Astrofísica de Canarias (Tenerife, Spain) to model strong UV spectral lines, such as H i and He ii Ly-α, and Mg ii h and k, in the unmagnetized regime (Belluzzi & Trujillo Bueno 2012; Belluzzi *et al.* 2012; Belluzzi & Trujillo Bueno 2014).

A complementary task has been tackled by Štěpán & Trujillo Bueno (2013), addressing the creation of scattering polarization and the Hanle effect in spectral lines formed in inhomogeneous and dynamic environments such as the solar chromosphere and transition region. Using their PORTA code, presently run on supercomputers to model the Ly-α line using the most recent three-dimensional magneto-hydrodynamic simulations of the solar atmosphere carried out at the University of Oslo (e.g. Carlsson *et al.* 2015), Štěpán *et al.* (2015) could successfully solve the non-LTE radiative transfer problem for polarized radiation in three-dimensional models of the solar atmosphere.

9. Research Highlights: Waves, Spicules, Ellerman Bombs

The ever increasing spatio-temporal resolution of modern telescopes and instrumentation has allowed the identification and study of a number of small-scale (sub-arcsecond) structures, mostly related to the presence of strong magnetic concentrations in the photosphere. The topic of how much such features and their dynamics can influence, or shape, the outer solar atmosphere remains of large interest.

9.1. *MHD waves*

Small-scale magnetic elements in the quiet Sun, such as magnetic bright points, are known to support a large number of magneto-hydrodynamic (MHD) waves. These waves, which come in a number of forms (kink, sausage, Alfvén) and are omnipresent in the Sun's atmosphere, are believed to contribute to the energy budgets of the chromosphere and corona: the details of which have remained a puzzle for more than a half-century. The last three years however, have seen several advances in our understanding of the characteristics and dynamics of MDH waves, and their potential for contributing to the heating of the Sun's outer layers. Jess *et al.* (2012a) used a combination of observations and numerical simulations to show that the vast majority of magnetic bright point structures demonstrate the signatures of upward propagating magneto-acoustic waves. This result sheds light on why MHD wave phenomena are so prevalent in the outer regions of the solar atmosphere. Studies of the propagation of kink waves through the solar atmosphere revealed dissipation of the waves between the chromosphere and corona (Morton *et al.* 2014), but not in the lower atmosphere (Stangalini *et al.* 2015). This suggests that the energy contained in MHD kink waves in small magnetic elements flows entirely to the upper layers of the Sun's atmosphere. With magnetic bright points covering about 2% of quiet Sun locations (Sánchez Almeida *et al.* 2010), it is not unreasonable to speculate that the generation of kink motions in small-scale magnetic fields may be responsible for the delivery of significant energy to higher atmospheric layers (Verth & Jess 2015).

There were several key investigations that revealed the mechanisms responsible for exciting kink waves. Stangalini *et al.* (2013, 2014) showed that convective buffeting of small magnetic elements produces both kink waves and longitudinal magneto-acoustic oscillations. The latter, which can appear through non-linear interactions with the transverse kink waves (Stangalini *et al.* 2013), are also observed to undergo longitudinal-to-transverse mode conversion into kink waves (Jess *et al.* 2012b). Finally, Morton *et al.* (2013) showed that the vortex motions of strong magnetic flux concentrations in the solar photosphere could act as sources of kink waves.

Moving onto studies of sausage waves, Jess *et al.* (2012b) showed that thin magnetic structures also support sausage- mode wave generation and propagation, while Moreels & Van Doorsselaere (2013); Moreels *et al.* (2013) developed a technique that allows the characterization of the different types of sausage-mode waves. Lastly, moving onto Alfvén waves, Asgari-Targhi & van Ballegooijen (2012) showed that random displacements of the photospheric anchor points of the magnetic field lines have the potential to induce significant wave turbulence that may create an efficient dissipation mechanism for Alfvén waves. If verified, this could have a large impact on solving the coronal heating enigma, as Alfvén waves have historically been considered a primary candidate for the transfer of convective energy at photospheric heights to the outer atmosphere, but there has always been a lack of identification of an effective dissipation mechanism. Interestingly, Chitta *et al.* (2012) detected significant power associated with high-frequency horizontal motions of bright points and suggested that this phenomenon may be important in the creation of a turbulent environment that promotes Alfvén wave dissipation (Verth & Jess 2015).

The presence of MHD waves in sunspots has been revisited by recent investigations using the powerful diagnostics afforded by imaging spectro-polarimetry using Fabry-Perot based instruments such as IBIS (Cavallini 2006) CRISP (Scharmer *et al.* 2008). The analysis of umbral flashes (UFs) by de la Cruz Rodríguez *et al.* (2013) showed that the typical reversal observed in the Stokes V profiles of chromospheric lines with a 3-minute periodicity (e.g. Socas-Navarro *et al.* 2000) is due to the passage of shocks that lead to a temperature excess up to 1000 K, while the magnetic field remains essentially unaltered. The shocks are only a fraction of an arcsec in lateral size, and derive from upward-propagating, slow magnetoacoustic modes induced by photospheric p-mode oscillations, as confirmed with IRIS data by Madsen *et al.* (2015). The same conclusions apply to the presence and properties of running penumbral waves, as due to the propagation of slow-mode waves along inclined field lines; Löhner-Böttcher & Bello González (2015) provide a clear evidence for the presence of such waves already at photospheric levels.

9.2. *Spicules, fibrils and and jets*

"Type-II spicules", slender and elongated jet-like events observed at the solar limb in chromospheric lines, have continued to attract much attention. Their most defining characteristics is that of rapidly disappearing along most of their length; this has been taken as indication of rapid heating to much higher temperatures, making them a possible important link between the corona and the chromosphere (De Pontieu *et al.* 2009, 2011).

Using a large dataset of *Hinode* Ca II H limb observations, Pereira *et al.* (2012) showed that type II spicules are the most common type, best observed in quiet Sun and coronal holes, while type-I spicules (see below) are limited to active-regions periphery. The use of imaging spectro-polarimeters (IBIS and CRISP) for disk observations has provided evidence that type-II spicules are readily observed on the solar disk as rapid variations in the far wings of Hα or Ca II lines (so called RBEs, Langangen *et al.* 2008; Sekse *et al.* 2012; Kuridze *et al.* 2015; Deng *et al.* 2015).(Quasi-)simultaneous spectroscopy in these two lines has further shown that spicules (RBEs) undergo torsional motions (De Pontieu *et al.* 2012) and also that they might appear sequentially in lines formed at progressively higher temperature (Sekse *et al.* 2013). Recent IRIS observations also indicate that type-II spicules become visible in transition region lines after fading from chromospheric passbands, thus strongly suggesting heating to at least 0.5–1 $\times$ 10^5 K (Pereira *et al.* 2014; Rouppe van der Voort *et al.* 2015). Caution should however be exercised in assigning precise temperature values to to such diagnostics, as effects of non-equilibrium ionization appear to be relevant in typical TR conditions (i.e. at temperatures where hydrogen is mostly ionized, see Olluri *et al.* 2015).

Some of the spicular properties determined from IRIS data also depict a less clear-cut scenario than before. For example, using an image enhancing analysis, Skogsrud *et al.* (2015a) show that spicules often appear co-temporally and co-spatially in both chromospheric and TR plasma, contrary to previous findings. Further, IRIS spicules show an obvious parabolic trajectory along their axis (Pereira *et al.* 2014; Skogsrud *et al.* 2015a), a signature that until now was univocally associated with magneto-acoustic shocks and dynamic fibrils, a supposedly very different phenomenon. Questions also still exist on the actual role and structure of type-II spicules in the coronal environment. Hydrodynamics calculations by Judge *et al.* (2012a) predict that the heating needed to produce coronal plasma from the cool spicular plasma would cause the velocity distributions of chromospheric and coronal lines to differ substantially, which is yet un-observed. Similarly, by assuming that all coronal plasma comes from spicules and considering the relevant observational consequences, Klimchuk (2012) concludes that spicules can provide only a small fraction of the hot plasma that exists in the corona. Finally, Judge *et al.* (2012b); Lipartito *et al.* (2014) present observations of spicules appearing almost at once along their entire length (several Mm), which would imply speeds much larger than the Alfvén velocity. They speculate that, rather than plasma accelerated in a flux-tube, such features are due to optical superposition of chromospheric plasma restricted to two-dimensional sheet-like structures, probably related to magnetic tangential discontinuities.

The driver of type II spicules also remains unclear. From disk observations of RBEs, they are reported to occur in small scale new magnetic concentrations in close proximity to network fields (Yurchyshyn *et al.* 2013; Deng *et al.* 2015), although the latter authors caution that an automatic approach recognizing both RBEs and magnetic cancellation yields a correlation with no better than random probability. A spicule-like jet appears in the 3D radiative-MHD simulation of Martínez-Sykora *et al.* (2011), as due to a strong Lorentz force squeezing the chromospheric material and propelling the spicule along the magnetic field (see also Goodman 2014). However, several of the reported observational properties of spicules are not well reproduced in the simulations (Martínez-Sykora *et al.* 2013); it is also worth of notice that despite the observational pervasiveness of spicules, radiative-MHD simulations so far have produced only one instance of type-II-like spicular material.

While many unknowns still persist about type-II spicules, our understanding of the origin and structure of so called dynamic fibrils, or “type I” spicules, has instead consolidated in the last years. Numerous proofs have by now been provided that this short lived phenomenon, well observed in the core of Hα and other chromospheric lines in the general vicinity of active regions, is due to (magneto-)acoustic shocks, developing at chromospheric heights as a consequence of the propagation of acoustic waves along field lines (see e.g. the review by Tsiropoula *et al.* 2012). Recent IRIS observations confirm the presence of dynamic fibrils also in Si IV and C II lines, as due to the excitation of the transition region by chromospheric shocks (Skogsrud *et al.* 2015b).

IRIS imaging and spectroscopy have also allowed a fresh view on the issue of transition region jets originating from the network edges, first reported by Hassler *et al.* (1999) from SUMER data, and related to the acceleration of the fast solar wind. Tian *et al.* (2014b) present observations of numerous, intermittent jets visible in the Si IV lines, which display upward speeds of 80–250 km s^{-1}, widths of $\approx$ 300 km, and extend to great heights, up to 10-15 Mm. These jets are especially well visible in coronal holes on disk, and have very brief lifetimes of 20–80 s. Assuming that all jet plasma contributes to the solar wind, the mass loss could amply compensate the total mass loss rate of the solar wind, although sensitive, concomitant coronal observations would be needed to confirm this. Also the energy flux of Alfvén waves carried by the jets (4–24 kW m^{-2}) is much larger than that required to drive the solar wind ($\approx$700 W m^{-2}), but the fraction dissipated by the jets is currently not known. Several reported properties of these jets are more extreme than those observed in type-II spicules; yet enough similarities seem to exist (e.g. the width, or their occurrence around the network edges) to warrant further investigation on a possible correspondence between the two phenomena.

9.3. *Ellerman bombs*

Ellerman bombs (EBs), small-scale brightenings that are usually observed in the Hα far wings, have been intensively investigated in recent years with high resolution observations. High resolution data revealed more abundant EBs than previously detected, and their energy distribution was found to follow a power law (Nelson *et al.* 2013a).

Spectral observations showed that EBs can also be detected in other lines like Ca ɪɪ H and K (Berlicki & Heinzel 2014; Li *et al.* 2015) and even in UV continuum (Vissers *et al.* 2013), but not in optical continuum and Mg ɪ b and Na ɪ D lines (Rutten *et al.* 2015). Considering the different emission features in line core and wings, a two-cloud model was applied to fit the typical Hα profile of EBs (Hong *et al.* 2014). Based on more sophisticated non-LTE calculations, the EB spectra can be reproduced by atmospheric models with a temperature hump in the lower chromosphere and temperature minimum region. The local temperature increase varies from hundreds to thousands of Kelvins (Berlicki & Heinzel 2014; Li *et al.* 2015).

EBs are usually accompanied with surges or jets (Yan *et al.* 2015; Reid *et al.* 2015). Spectro-polarimetric observations showed that EBs occur at sites of opposite magnetic polarities (Bello González *et al.* 2013) or flux cancellation (Vissers *et al.* 2013). These observations strongly suggest that EBs originate from magnetic reconnection in the photosphere (Reid *et al.* 2015). The most interesting finding is probably that EBs are also visible in UV lines observed by IRIS (Vissers *et al.* 2015) with formation temperatures almost one order of magnitude higher than what the usual semi-empirical models predict. Whether EBs are really so hot and how they are related to the hot explosions detected in the cool atmosphere (Peter *et al.* 2014) will be an interesting topic in the following years.

10. Research Highlights: Multidimensional numerical modeling of the solar convection zone and atmosphere

The numerical modeling of astrophysical processes is taking advantage of the extremely fast progress in the capabilities of massively-parallel supercomputing installations. The solar community is particularly active in producing highly sophisticated computer codes that can exploit the advances in the supercomputing equipments. Multidimensional numerical models that solve the equations of magnetofluid dynamics are being produced, that tackle an ever increasing range of problems in the solar atmosphere and interior. In many cases they also simultaneously deal with the associated, complex radiation transfer aspects.

In the following, a number of selected highlights of the past few years are presented that can illustrate the pace of advance in this field.

10.1. *The solar dynamo problem*

Realistic radiation-magnetoconvection models with extremely high spatial resolution showing a local dynamo effect in the topmost several Mm of the solar interior have been produced (Rempel 2014; Kitiashvili *et al.* 2015). Their results contribute to the question of whether the magnetic flux seen in the quiet Sun is independently generated in the topmost levels of the convection zone, or whether one should see it just as being the surface manifestation of the global dynamo action taking place in the whole solar convection zone (see the discussion, e.g., in the paper by Stein 2012).

Concerning large-scale dynamo action, recent results obtained through purely MHD numerical models are those by Cattaneo & Tobias (2014) and those summarized in the review by Brandenburg *et al.* (2012b). Also, both Nelson *et al.* (2013b) and Fan & Fang (2014) obtain dynamo action in a 3D spherical model of large-scale magnetoconvection obtained solving the MHD equations in the anelastic approximation. Those calculations lead to the concentration of the field (a) as *magnetic wreaths* in the bulk of the convection zone (Nelson *et al.* 2013b) or (b) at its bottom (Fan & Fang 2014) and both produce strong-field emerging magnetic structures at (or rising toward) the top of their domain. Concerning the rise of magnetic tubes toward the solar surface, Jouve & Brun (2009) and Jouve *et al.* (2013) study the detailed interaction of buoyant tubes initially located at the bottom of the domain (i.e., not obtained via a dynamo mechanism) with self-consistent 3D giant convection cells and confirm some of the results previously obtained with simple 1D thin flux tube models.

Pipin & Kosovichev (2013) investigated the properties of a mean-field solar dynamo with the double-cell meridional circulation. Contrary to the flux-transport models (Hazra *et al.* 2014), they found that such dynamo model can robustly reproduce basic properties of the solar magnetic cycles. The best agreement with observations is achieved when the surface meridional circulation speed is about 12 m s^{-1}.

Finally, Guerrero *et al.* (2013) performed three-dimensional anelastic simulations for global solar models, and found that the models with the solar-like differential rotation tend to produce multiple cells of meridional circulation. They confirmed results of previous simulations that the large convective cells are aligned along the rotation axis in the deep convection zone, and suggested that such 'banana-cell' pattern can be hidden beneath the supergranulation layer.

10.2. *Magnetic flux emergence near the surface. Active region formation.*

The actual process that makes sunspots and active regions appear as concentrated magnetic structures at, and near, the surface has been discussed by various authors in the past few years. A. Nordlund, R. Stein and collaborators are carrying out radiation-MHD convection simulations with boxes extending from the photosphere down to a few tens of Megameters depth in the convection zone (e.g. Stein *et al.* 2012; Georgobiani *et al.* 2012; Stein & Nordlund 2014). They inject an extended field distribution through the bottom boundary. When the injected flux is already in the top levels of the box, the magnetic flux is gathered in pore-like features through the convection flows alone. Detailed models for the formation of active regions in a realistic magnetoconvection setup have also been produced by Rempel & Cheung (2014) as well as by Fang *et al.* (2012) and Fang & Fan (2015). An alternative mechanism for the concentration of magnetic flux into sunspot-like structures has been proposed by A. Brandenburg and collaborators: using idealized pure-MHD models, these authors have recently discussed the so called *negative effective magnetic pressure instability* or *nempi* for short (Brandenburg *et al.* 2012a; Kemel *et al.* 2013), that can lead to the formation of concentrated magnetic structures in a turbulent domain.

10.3. *3D models for the atmosphere*

Multidimensional numerical simulation of structures and processes in the solar atmosphere is also producing models of increasing accuracy and realism. For example, an important branch is growing that deals with the formation of prominences: the condensation of the prominence material has been modeled in three spatial dimensions by Xia *et al.* (2014) and Keppens *et al.* (2015) via a thermal instability mechanism and by Knizhnik *et al.* (2015) via the helicity condensation mechanism of Antiochos (2013).

Building on earlier models (e.g. Gudiksen & Nordlund 2005), Gudiksen *et al.* (2011) presented a massively parallel numerical code, Bifrost, for simulating stellar atmospheres from the convection zone to the corona. Simulated atmospheres including various magnetic field topologies have since been produced to study different aspects of the outer solar atmosphere, the chromosphere in particular. By coupling the numerical simulations with 3D non-LTE radiative transfer computations, Leenaarts *et al.* (2012) could successfully investigate the Hα line formation in the chromosphere, and reproduce for the first time the appearance and properties of the fibrils usually observed in active regions. One of their important results was that the model atmosphere must properly take into account the non-equilibrium ionization of hydrogen. In a follow-up work, the same authors highlight how the Hα fibrils trace magnetic filed lines only partially, with a typical timescale of $\sim$ 200 s (Leenaarts *et al.* 2015). Recently, Carlsson *et al.* (2015) have made available the results of one such simulation, with a magnetic field topology similar to an enhanced network area on the Sun.

The effects of the interactions between ions and neutral particles in the partially ionized chromosphere have been studied by a number of authors. Martínez-Sykora *et al.* (2012) found that Ohmic diffusion, Hall term, and ambipolar diffusion show strong variations in the chromosphere, with ambipolar diffusion providing the strongest impact to the model atmosphere. This confirmed the earlier conclusions of Khomenko & Collados (2012), obtained via both numerical simulations and analytical estimates, that ambipolar diffusion can efficiently dissipate magnetic energy at chromospheric levels, increasing the minimum temperature in the chromosphere. A generalized review of the physical coupling of ionized plasma and neutral gas in the weakly ionized Sun's chromosphere and Earth's ionosphere/thermosphere has been presented by Leake *et al.* (2014).

Finally, the atmosphere is the site of a multitude of eruptions and jets of various sizes, especially the chromosphere and corona. Chromospheric jets, spicules and cool surges have been modeled in the past few years using different levels of approximation and realism, from pure MHD in two dimensions with or without heat conduction and optically thin cooling (Jiang *et al.* 2012; Kayshap *et al.* 2013a,b; Takasao *et al.* 2013; Yang *et al.* 2013) to realistic three-dimensional OSC or Bifrost simulations including radiative transfer by Martínez-Sykora *et al.* (2011, 2013) for type-II spicules and by Archontis & Hansteen (2014) for clusters of microflares. The classical EUV/X-Ray jets typically observed in coronal holes or at the fringes of active regions have been the subject of intense numerical modeling activity. In the past few years, two major alternative jet models have received much attention, namely the jet launch following flux emergence (Moreno-Insertis & Galsgaard 2013; Fang *et al.* 2014) and a mechanism related with the rotation of field lines via photospheric driving (Pariat *et al.* 2015). Of special interest are the physical processes in the eruptive phase of the so-called blowout jets (Moore *et al.* 2010; Liu *et al.* 2011; Madjarska 2011). The eruptions could be due to the development of a tether-cutting instability in the domain below the quiescent jet (as discussed by Archontis & Hood 2013; Archontis *et al.* 2014; Lee *et al.* 2015) or to tether-cutting followed by other instability mechanisms (Moreno-Insertis & Galsgaard 2013).

11. Final remarks

The collection of “IAU Transactions A” reports provided by the three solar IAU commissions, as described in Sect. 2, represents a comprehensive view of more than 50 years of solar physics. As listed in Table 1, the majority of these reports is available online, but some can currently be found only in the printed Volumes of IAU Transactions A. To properly acknowledge the efforts of our predecessors, Division E plans to collect all the past reports in digital form and ensure that these are discoverable through, e.g., ADS, so that a complete, composite record is available to future Commissions.

Gianna Cauzzi
President of the Commission

Acknowledgement

We thank L. Belluzzi and T. Riethmüller for contributions to this text. Dr. Lidia van Driel-Gesztelyi, President of Division E during the 2012-2015 period, has been a constant source of help and inspiration in navigating IAU activities.

References

Adelberger, E. G., García, A., Robertson, R. G. H., *et al.* 2011, *Reviews of Modern Physics*, 83, 195

Antiochos, S. K. 2013, *ApJ* , 772, 72

Archontis, V. & Hansteen, V. 2014, *ApJ*, 788, L2

Archontis, V. & Hood, A. W. 2013, *ApJ*, 769, L21

Archontis, V., Hood, A. W., & Tsinganos, K. 2014, *ApJ*, 786, L21

Asgari-Targhi, M. & van Ballegooijen, A. A. 2012, *ApJ* , 746, 81

Asplund, M., Grevesse, N., Sauval, A. J., Allende Prieto, C., & Kiselman, D. 2004, *A& A*, 417, 751

Athay, R. G., Pierce, A. K., & Rigutti, M. 1970, *Transactions of the International Astronomical Union*, Series A, 14, 111

Ball, W. T., Krivova, N. A., Unruh, Y. C., Haigh, J. D., & Solanki, S. K. 2014, *Journal of Atmospheric Sciences*, 71, 4086

Bello González, N., Danilovic, S., & Kneer, F. 2013, *A& A*, 557, A102

Belluzzi, L. & Trujillo Bueno, J. 2012, *ApJ*, 750, L11

—. 2014, *A& A*, 564, A16

Belluzzi, L., Trujillo Bueno, J., & Štěpán, J. 2012, *ApJ*, 755, L2

Berlicki, A. & Heinzel, P. 2014, *A& A*, 567, A110

Bianda, M., Ramelli, R., Gisler, D., & Stenflo, J. O. 2014, in *Astronomical Society of the Pacific Conference Series*, Vol. 489, Solar Polarization 7, ed. K. N. Nagendra, J. O. Stenflo, Q. Qu, & M. Samooprna, 167

Bolduc, C., Charbonneau, P., Barnabé, R., & Bourqui, M. S. 2014, *Sol. Phys.*, 289, 2891

Bommier, V. 1997a, *A& A*, 328, 706

—. 1997b, *A& A*, 328, 726

Bonanno, A. & Fröhlich, H.-E. 2015, *A& A*, 580, A130

Brandenburg, A., Kemel, K., Kleeorin, N., & Rogachevskii, I. 2012a, *ApJ* , 749, 179

Brandenburg, A., Sokoloff, D., & Subramanian, K. 2012b, *Space Sci. Rev.*, 169, 123

Brosius, J. W., Daw, A. N., & Rabin, D. M. 2014, *ApJ* , 790, 112

Caffau, E., Ludwig, H.-G., Steffen, M., *et al.* 2015, *A& A*, 579, A88

Carlsson, M., Hansteen, V. H., Gudiksen, B. V., Leenaarts, J., & De Pontieu, B. 2015, ArXiv e-prints

Casini, R., Landi Degl'Innocenti, M., Manso Sainz, R., Landi Degl'Innocenti, E., & Landolfi, M. 2014, *ApJ* , 791, 94

Cattaneo, F. & Tobias, S. M. 2014, *ApJ* , 789, 70

Cavallini, F. 2006, *Sol. Phys.*, 236, 415

Chitta, L. P., van Ballegooijen, A. A., Rouppe van der Voort, L., DeLuca, E. E., & Kariyappa, R. 2012, *ApJ* , 752, 48

Cirtain, J. W., Golub, L., Winebarger, A. R., *et al.* 2013, *Nature*, 493, 501

Criscuoli, S. & Uitenbroek, H. 2014, *ApJ* , 788, 151

Danilovic, S., Hirzberger, J., Riethmüller, T. L., *et al.* 2014, *ApJ* , 784, 20

Dasi-Espuig, M., Jiang, J., Krivova, N. A., & Solanki, S. K. 2014, *A& A*, 570, A23

de la Cruz Rodríguez, J., Rouppe van der Voort, L., Socas-Navarro, H., & van Noort, M. 2013, *A& A*, 556, A115

de la Cruz Rodríguez, J. & Socas-Navarro, H. 2011, *A& A*, 527, L8

De Pontieu, B., Carlsson, M., Rouppe van der Voort, L. H. M., *et al.* 2012, *ApJ*, 752, L12

De Pontieu, B., McIntosh, S. W., Hansteen, V. H., & Schrijver, C. J. 2009, *ApJ*, 701, L1

De Pontieu, B., McIntosh, S. W., Carlsson, M., *et al.* 2011, *Science*, 331, 55

De Pontieu, B., Title, A. M., Lemen, J. R., *et al.* 2014, *Sol. Phys.*, 289, 2733

Deland, M. T. & Cebula, R. P. 2012, *Journal of Atmospheric and Solar-Terrestrial Physics*, 77, 225

Deng, N., Chen, X., Liu, C., *et al.* 2015, *ApJ* , 799, 219

Domingo, V., Ermolli, I., Fox, P., *et al.* 2009, *Space Sci. Rev.*, 145, 337

Dominique, M., Hochedez, J.-F., Schmutz, W., *et al.* 2013, *Sol. Phys.*, 286, 21

Ermolli, I., Matthes, K., Dudok de Wit, T., *et al.* 2013, *Atmospheric Chemistry & Physics*, 13, 3945

Fabbian, D. & Moreno-Insertis, F. 2015, *ApJ* , 802, 96

Fan, Y. & Fang, F. 2014, *ApJ* , 789, 35

Fang, C., Chen, P.-F., Li, Z., *et al.* 2013, Research in *Astronomy and Astrophysics*, 13, 1509

Fang, F. & Fan, Y. 2015, *ApJ* , 806, 79

Fang, F., Fan, Y., & McIntosh, S. W. 2014, *ApJ*, 789, L19

Fang, F., Manchester, IV, W., Abbett, W. P., & van der Holst, B. 2012, *ApJ* , 745, 37

Fehlmann, A., Kopp, G., Schmutz, W., *et al.* 2012, *Metrologia*, 49, 34

Fröhlich, C. 2012, *Surveys in Geophysics*, 33, 453

Georgobiani, D., Stein, R., & Nordlund, A. 2012, IAU Special Session, 6, 102

Goodman, M. L. 2014, *ApJ* , 785, 87

Gošić, M., Bellot Rubio, L. R., Orozco Suárez, D., Katsukawa, Y., & del Toro Iniesta, J. C. 2014, *ApJ* , 797, 49

Graham, D. R. & Cauzzi, G. 2015, *ApJ*, 807, L22

Grevesse, N., Scott, P., Asplund, M., & Sauval, A. J. 2015, *A& A*, 573, A27

Gudiksen, B. V., Carlsson, M., Hansteen, V. H., *et al.* 2011, *A& A*, 531, A154

Gudiksen, B. V. & Nordlund, Å. 2005, *ApJ* , 618, 1020

Guerrero, G., Smolarkiewicz, P. K., Kosovichev, A. G., & Mansour, N. N. 2013, *ApJ* , 779, 176

Harder, J. W., Fontenla, J. M., Pilewskie, P., Richard, E. C., & Woods, T. N. 2009, Geophys. Res. Lett., 36, 7801

Hassler, D. M., Dammasch, I. E., Lemaire, P., *et al.* 1999, *Science*, 283, 810

Hathaway, D. H. 2012, *ApJ*, 749, L13

Hathaway, D. H. & Upton, L. 2014, Journal of Geophysical Research (Space Physics), 119, 3316

Hathaway, D. H., Upton, L., & Colegrove, O. 2013, *Science*, 342, 1217

Hazra, G., Karak, B. B., & Choudhuri, A. R. 2014, *ApJ* , 782, 93

Hong, J., Ding, M. D., Li, Y., Fang, C., & Cao, W. 2014, *ApJ* , 792, 13

Howe, R., Komm, R. W., Baker, D., *et al.* 2015, ArXiv e-prints

Ishikawa, R., Kano, R., Winebarger, A., *et al.* 2015, *IAU General Assembly*, 22, 54536

Jafarzadeh, S., Solanki, S. K., Lagg, A., *et al.* 2014, *A& A*, 569, A105

Jess, D. B., Pascoe, D. J., Christian, D. J., *et al.* 2012a, *ApJ*, 744, L5

Jess, D. B., Shelyag, S., Mathioudakis, M., *et al.* 2012b, *ApJ* , 746, 183

Jiang, R.-L., Fang, C., & Chen, P.-F. 2012, *ApJ* , 751, 152

Jin, C. & Wang, J. 2015, *ApJ* , 806, 174

Jouve, L. & Brun, A. S. 2009, *ApJ* , 701, 1300

Jouve, L., Brun, A. S., & Aulanier, G. 2013, *ApJ* , 762, 4

Judge, P. G., de Pontieu, B., McIntosh, S. W., & Olluri, K. 2012a, *ApJ* , 746, 158

Judge, P. G., Reardon, K., & Cauzzi, G. 2012b, *ApJ*, 755, L11

Kayshap, P., Srivastava, A. K., & Murawski, K. 2013a, *ApJ* , 763, 24

Kayshap, P., Srivastava, A. K., Murawski, K., & Tripathi, D. 2013b, *ApJ*, 770, L3

Kemel, K., Brandenburg, A., Kleeorin, N., Mitra, D., & Rogachevskii, I. 2013, *Sol. Phys.*, 287, 293

Keppens, R., Xia, C., & Porth, O. 2015, *ApJ*, 806, L13

Kholikov, S., Serebryanskiy, A., & Jackiewicz, J. 2014, *ApJ* , 784, 145

Khomenko, E. & Collados, M. 2012, *ApJ* , 747, 87

Kitiashvili, I. N., Kosovichev, A. G., Mansour, N. N., & Wray, A. A. 2015, *ApJ* , 809, 84

Kleint, L., Shapiro, A. I., Berdyugina, S. V., & Bianda, M. 2011, *A& A*, 536, A47

Klimchuk, J. A. 2012, *Journal of Geophysical Research* (Space Physics), 117, 12102

Knizhnik, K. J., Antiochos, S. K., & DeVore, C. R. 2015, *ApJ* , 809, 137
Komm, R., González Hernández, I., Howe, R., & Hill, F. 2015a, *Sol. Phys.*
—. 2015b, *Sol. Phys.*, 290, 1081
Kopp, G. 2014, *Journal of Space Weather and Space Climate*, 4, A14
Kuridze, D., Henriques, V., Mathioudakis, M., *et al.* 2015, *ApJ* , 802, 26
Kuznetsov, V. D., Zelenyi, L. M., Zimovets, I. V. *et al.*, *Geomagnetism and Aeronomy*, 2016, in press.
Lagg, A., Lites, B., Harvey, J., Gosain, S., & Centeno, R. 2015, ArXiv e-prints
Landi Degl'Innocenti, E., Landi Degl'Innocenti, M., & Landolfi, M. 1997, in Science with THÉMIS, eds. N. Mein, and S. Sahal-Bréchot (Paris: Obs. Paris-Meudon), 59
Langangen, Ø., De Pontieu, B., Carlsson, M., *et al.* 2008, *ApJ*, 679, L167
Leake, J. E., DeVore, C. R., Thayer, J. P., *et al.* 2014, *Space Sci. Rev.*, 184, 107
Lee, E. J., Archontis, V., & Hood, A. W. 2015, *ApJ*, 798, L10
Leenaarts, J., Carlsson, M., & Rouppe van der Voort, L. 2012, *ApJ* , 749, 136
—. 2015, *ApJ* , 802, 136
Li, Z., Fang, C., Guo, Y., *et al.* 2015, *Research in Astronomy and Astrophysics*, 15, 1513
Lipartito, I., Judge, P. G., Reardon, K., & Cauzzi, G. 2014, *ApJ* , 785, 109
Liu, C., Deng, N., Liu, R., *et al.* 2011, *ApJ*, 735, L18
Liu, Z., Xu, J., Gu, B.-Z., *et al.* 2014, *Research in Astronomy and Astrophysics*, 14, 705
Löhner-Böttcher, J. & Bello González, N. 2015, *A& A*, 580, A53
Madjarska, M. S. 2011, *A& A*, 526, A19
Madsen, C. A., Tian, H., & DeLuca, E. E. 2015, *ApJ* , 800, 129
Marchenko, S. V. & DeLand, M. T. 2014, *ApJ* , 789, 117
Martínez González, M. J., Bellot Rubio, L. R., Solanki, S. K., *et al.* 2012, *ApJ*, 758, L40
Martínez Pillet, V., Del Toro Iniesta, J. C., Álvarez-Herrero, A., *et al.* 2011, *Sol. Phys.*, 268, 57
Martínez-Sykora, J., De Pontieu, B., & Hansteen, V. 2012, *ApJ* , 753, 161
Martínez-Sykora, J., Hansteen, V., & Moreno-Insertis, F. 2011, *ApJ* , 736, 9
Martínez-Sykora, J., De Pontieu, B., Leenaarts, J., *et al.* 2013, *ApJ* , 771, 66
Moore, R. L., Cirtain, J. W., Sterling, A. C., & Falconer, D. A. 2010, *ApJ* , 720, 757
Moreels, M. G., Goossens, M., & Van Doorsselaere, T. 2013, *A& A*, 555, A75
Moreels, M. G. & Van Doorsselaere, T. 2013, *A& A*, 551, A137
Moreno-Insertis, F. & Galsgaard, K. 2013, *ApJ* , 771, 20
Morrill, J. S., Floyd, L., & McMullin, D. 2014, *Sol. Phys.*, 289, 3641
Morton, R. J., Verth, G., Fedun, V., Shelyag, S., & Erdélyi, R. 2013, *ApJ* , 768, 17
Morton, R. J., Verth, G., Hillier, A., & Erdélyi, R. 2014, *ApJ* , 784, 29
Narendranath, S., Sreekumar, P., Alha, L., *et al.* 2014, *Sol. Phys.*, 289, 1585
Nelson, C. J., Doyle, J. G., Erdélyi, R., *et al.* 2013a, *Sol. Phys.*, 283, 307
Nelson, N. J., Brown, B. P., Brun, A. S., Miesch, M. S., & Toomre, J. 2013b, *ApJ* , 762, 73
Olluri, K., Gudiksen, B. V., Hansteen, V. H., & De Pontieu, B. 2015, *ApJ* , 802, 5
Orozco Suárez, D., Asensio Ramos, A., & Trujillo Bueno, J. 2014, *A& A*, 566, A46
—. 2015, *ApJ*, 803, L18
Pariat, E., Dalmasse, K., DeVore, C. R., Antiochos, S. K., & Karpen, J. T. 2015, *A& A*, 573, A130
Pereira, T. M. D., De Pontieu, B., & Carlsson, M. 2012, *ApJ* , 759, 18
Pereira, T. M. D., De Pontieu, B., Carlsson, M., *et al.* 2014, *ApJ*, 792, L15
Peter, H., Tian, H., Curdt, W., *et al.* 2014, *Science*, 346, 1255726
Pipin, V. V. & Kosovichev, A. G. 2013, *ApJ* , 776, 36
Ramelli, R., Bianda, M., Berdyugina, S., Stenflo, J. O., & Belluzzi, L. 2015, *IAU General Assembly*, 22, 57074
Reid, A., Mathioudakis, M., Scullion, E., *et al.* 2015, *ApJ* , 805, 64
Reiter, J., Rhodes, Jr., E. J., Kosovichev, A. G., *et al.* 2015, *ApJ* , 803, 92
Rempel, M. 2014, *ApJ* , 789, 132
Rempel, M. & Cheung, M. C. M. 2014, *ApJ* , 785, 90
Riethmüller, T. L., Solanki, S. K., Berdyugina, S. V., *et al.* 2014, *A& A*, 568, A13

Riethmüller, T. L., Solanki, S. K., Hirzberger, J., *et al.* 2013, *ApJ*, 776, L13
Rimmele, T., McMullin, J., Warner, M., *et al.* 2015, *IAU General Assembly*, 22, 55176
Rouppe van der Voort, L., De Pontieu, B., Pereira, T. M. D., Carlsson, M., & Hansteen, V. 2015, *ApJ*, 799, L3
Rutten, R. J., Rouppe van der Voort, L. H. M., & Vissers, G. J. M. 2015, *ApJ* , 808, 133
Salabert, D., García, R. A., & Turck-Chièze, S. 2015, *A& A*, 578, A137
Sánchez Almeida, J., Bonet, J. A., Viticchié, B., & Del Moro, D. 2010, *ApJ*, 715, L26
Schad, A., Timmer, J., & Roth, M. 2013a, *ApJ*, 778, L38
Schad, T. A., Penn, M. J., & Lin, H. 2013b, *ApJ* , 768, 111
Schad, T. A., Penn, M. J., Lin, H., & Tritschler, A. 2015, *Sol. Phys.*, 290, 1607
Scharmer, G. B., Narayan, G., Hillberg, T., *et al.* 2008, *ApJ*, 689, L69
Schmidtke, G. 2015, History of Geo- and Space Sciences, 6, 3
Schmutz, W., Fehlmann, A., Finsterle, W., Kopp, G., & Thuillier, G. 2013, in *American Institute of Physics Conference Series*, Vol. 1531, American Institute of Physics Conference Series, 624–627
Schrijver, C. J., Fletcher, L., van Driel-Gesztelyi, L., *et al.* 2015, ArXiv e-prints
Scott, P., Asplund, M., Grevesse, N., Bergemann, M., & Sauval, A. J. 2015a, *A& A*, 573, A26
Scott, P., Grevesse, N., Asplund, M., *et al.* 2015b, *A& A*, 573, A25
Sekse, D. H., Rouppe van der Voort, L., & De Pontieu, B. 2012, *ApJ* , 752, 108
—. 2013, *ApJ* , 764, 164
Shapiro, A. I., Solanki, S. K., Krivova, N. A., Tagirov, R. V., & Schmutz, W. K. 2015, *A& A*, 581, A116
Skogsrud, H., Rouppe van der Voort, L., De Pontieu, B., & Pereira, T. M. D. 2015, *ApJ* , 806, 170
Skogsrud, H., Rouppe van der Voort, L., & De Pontieu, B. 2015, *ApJ* , submitted
Smitha, H. N., Nagendra, K. N., Stenflo, J. O., *et al.* 2012a, *A& A*, 541, A24
Smitha, H. N., Nagendra, K. N., Stenflo, J. O., & Sampoorna, M. 2013, *ApJ* , 768, 163
Smitha, H. N., Sampoorna, M., Nagendra, K. N., & Stenflo, J. O. 2011, *ApJ* , 733, 4
Smitha, H. N., Sowmya, K., Nagendra, K. N., Sampoorna, M., & Stenflo, J. O. 2012b, *ApJ* , 758, 112
Snow, M., McClintock, W. E., & Woods, T. N. 2010, *Advances in Space Research*, 46, 296
Sobotka, M., Dudik, J., Denker, C., *et al.* 2015, *IAU General Assembly*, 22, 46841
Socas-Navarro, H. 2015, *A& A*, 577, A25
Socas-Navarro, H., Trujillo Bueno, J., & Ruiz Cobo, B. 2000, *ApJ* , 544, 1141
Solanki, S. K., Krivova, N. A., & Haigh, J. D. 2013, ARA&A, 51, 311
Sowmya, K., Nagendra, K. N., Stenflo, J. O., & Sampoorna, M. 2014, *ApJ* , 786, 150
Stangalini, M., Consolini, G., Berrilli, F., De Michelis, P., & Tozzi, R. 2014, *A& A*, 569, A102
Stangalini, M., Giannattasio, F., & Jafarzadeh, S. 2015, *A& A*, 577, A17
Stangalini, M., Solanki, S. K., Cameron, R., & Martínez Pillet, V. 2013, *A& A*, 554, A115
Stein, R. & Nordlund, A. 2014, in COSPAR Meeting, Vol. 40, 40th COSPAR Scientific Assembly, 3196
Stein, R. F. 2012, Living Reviews in Solar Physics, 9, 4
Stein, R. F., Lagerfjärd, A., Nordlund, Å., & Georgobiani, D. 2012, in Astronomical Society of the Pacific Conference Series, Vol. 462, Progress in Solar/Stellar Physics with Helio- and Asteroseismology, ed. H. Shibahashi, M. Takata, & A. E. Lynas-Gray, 345
Stenflo, J., ed. 1994, *Astrophysics and Space Science Library*, Vol. 189, Solar Magnetic Fields: Polarized Radiation Diagnostics
Sylwester, B., Phillips, K. J. H., Sylwester, J., & Kępa, A. 2013, *Sol. Phys.*, 283, 453
Sylwester, B., Sylwester, J., Phillips, K. J. H., Kępa, A., & Mrozek, T. 2014, *ApJ* , 787, 122
Sylwester, J., Sylwester, B., Phillips, K. J. H., & Kuznetsov, V. D. 2012, *ApJ* , 751, 103
Takasao, S., Isobe, H., & Shibata, K. 2013, PASJ, 65, 62
Testa, P., De Pontieu, B., Martínez-Sykora, J., *et al.* 2013, *ApJ*, 770, L1
Testa, P., De Pontieu, B., Allred, J., *et al.* 2014, *Science*, 346, 1255724
Thuillier, G., Schmidtke, G., Erhardt, C., *et al.* 2014a, *Sol. Phys.*, 289, 4433
Thuillier, G., Bolsée, D., Schmidtke, G., *et al.* 2014b, *Sol. Phys.*, 289, 1931

Tian, H., Li, G., Reeves, K. K., *et al.* 2014a, *ApJ*, 797, L14
Tian, H., DeLuca, E. E., Cranmer, S. R., *et al.* 2014b, *Science*, 346, 1255711
Trujillo Bueno, J., Štěpán, J., & Belluzzi, L. 2012, *ApJ*, 746, L9
Trujillo Bueno, J., Štěpán, J., & Casini, R. 2011, *ApJ*, 738, L11
Tsiropoula, G., Tziotziou, K., Kontogiannis, I., *et al.* 2012, *Space Sci. Rev.*, 169, 181
Usoskin, I. G., Arlt, R., Asvestari, E., *et al.* 2015, *A& A*, 581, A95
Štěpán, J. & Trujillo Bueno, J. 2013, *A& A*, 557, A143
Štěpán, J., Trujillo Bueno, J., Leenaarts, J., & Carlsson, M. 2015, *ApJ* , 803, 65
Verth, G. & Jess, D. B. 2015, ArXiv e-prints
Vissers, G. J. M., Rouppe van der Voort, L. H. M., & Rutten, R. J. 2013, *ApJ* , 774, 32
Vissers, G. J. M., Rouppe van der Voort, L. H. M., Rutten, R. J., Carlsson, M., & De Pontieu, B. 2015, *ApJ* , 812, 11
Wedemeyer, S., Bastian, T., Brajsa, R., *et al.* 2015, ArXiv e-prints
Wehrli, C., Schmutz, W., & Shapiro, A. I. 2013, *A& A*, 556, L3
Willson, R. C. 2014, Ap&SS, 352, 341
Wilson, P. R., Altrocki, R. C., Harvey, K. L., Martin, S. F., & Snodgrass, H. B. 1988, *Nature*, 333, 748
Woods, T. N., Eparvier, F. G., Bailey, S. M., *et al.* 2005, Journal of Geophysical Research (Space Physics), 110, 1312
Woods, T. N., Eparvier, F. G., Hock, R., *et al.* 2012, *Sol. Phys.*, 275, 115
Xia, C., Keppens, R., Antolin, P., & Porth, O. 2014, *ApJ*, 792, L38
Yan, X. L., Xue, Z. K., Pan, G. M., *et al.* 2015, ApJS, 219, 17
Yang, L., He, J., Peter, H., *et al.* 2013, *ApJ* , 777, 16
Yang, S., Zhang, J., & Xiang, Y. 2014, *ApJ*, 793, L28
Yeo, K. L., Ball, W. T., Krivova, N. A., *et al.* 2015, *Journal of Geophysical Research (Space Physics)*, 120, 6055
Yeo, K. L., Krivova, N. A., Solanki, S. K., & Glassmeier, K. H. 2014, *A& A*, 570, A85
Yurchyshyn, V., Abramenko, V., & Goode, P. 2013, *ApJ* , 767, 17
Zhao, J., Bogart, R. S., Kosovichev, A. G., Duvall, Jr., T. L., & Hartlep, T. 2013, *ApJ*, 774, L29
Zhao, J., Kosovichev, A. G., & Bogart, R. S. 2014, *ApJ*, 789, L7
Zolotova, N. V. & Ponyavin, D. I. 2015, *ApJ* , 800, 42